SUDBURY ENVIRONMENTAL STUDY

SHORT RANGE SHORT-TERM FUMIGATION MODEL FOR THE INCO SUPERSTACK

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by

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Abstract

This report presents a new model to predict the dispersion of pollutants emitted into the boundary layer associated with sunny days. The model is applicable to the INCO superstack plume which causes air quality problems, primarily during convective conditions, when atmospheric turbulence is generated by surface heating due to high incoming solar radiation. Under these conditions, conventional Gaussian models based on Pasquill-Gifford curves cannot be used to estimate ground level concentrations.

The model has been validated with field data collected in Sudbury and elsewhere. The input parameters of the model depend on routinely available meteorological measurements. So, it is ideally suited for utilization in a supplementary emission control system such as the one presently being operated at the International Nickel Company in Sudbury.

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1. INTRODUCTION

The 381 m superstack operated by the International Nickel Company (INCO) in Sudbury is the single largest point source of SO_2 in North America. On an average, it emits around 3000 tons of SO_2 every day. Due to the large buoyancy of the plume, the effective emission height is about 800 m from the ground. During most of the year the atmospheric boundary layer does not grow to this height and the plume is not brought down to the ground. However, during the daytime hours of the summer months (June to September) the boundary layer associated with surface heating by solar radiation grows to heights around 1000 m. The plume emitted into the turbulent boundary layer is then mixed down to the ground and high SO_2 concentrations can occur. Thus, in terms of local air quality, the emissions from the superstack are a problem primarily during hot summer days.

The atmospheric boundary layer in which turbulence is largely maintained by buoyancy originating from the surface heated by solar radiation is referred to as convective. The vigorous turbulence of the convective boundary layer leads to rapid mixing of pollutants emitted into it. It is only recently (Willis and Deardorff, 1978; Venkatram, 1980) that we have started to understand dispersion in the convective boundary layer. Conventional "Gaussian type" dispersion models cannot predict ground-level concentrations under such conditions.

In this report we describe a dispersion model to estimate concentrations associated with plumes emitted into the convective boundary layer. This model can be used in a supplementary emission control system for INCO.

We might point out that pollutants from stacks over 100 m tall are primarily affected by convective turbulence (Venkatram, 1980). This suggests that the model is applicable to most major pollutant sources in Ontario. Also, as high concentrations from these sources occur during convective conditions, the model is a vital component of long-term models.

2. The Model

Before describing the model it is useful to review some relevant features of the convective boundary layer. The turbulent velocities σ_v and σ_w in the upper part of the PBL ($z \geq 0.1\ z_i$) are proportional to the convective velocity scale w_* given by

$$w_* = (gH_o z_i / T_o)^{1/3} \qquad (1)$$

where H_o is the surface heat flux, T_o is the average temperature of the mixed layer and z_i is the mixed layer height. Thus, w_* is one of the controlling parameters for dispersion of pollutants emitted at heights much greater than the thickness of the shear dominated surface layer. We recall that this surface layer does not extend much higher than $z = |L|$ where L, the Monin-Obukhov length, is

$$L = -T_o u_*^3 / gkH_o \qquad (2)$$

In (2), u_* is the surface friction velocity and k is the von-Karman constant.

As the most energetic eddies in the mixed layer scale with z_i, the integral time scale τ_m relevant to dispersion is z_i/w_*. We also see that τ_m is roughly the time taken after release for pollutants to become well mixed through the depth of the mixed layer. This

interpretation of τ_m allows us to appreciate the definition of the non-dimensional travel distance X,

$$X \equiv w_* x / z_i u \qquad (3)$$

In (3), x is the distance from the pollutant source and u is the mean mixed layer wind.

With the preliminaries of the preceding paragraphs we are now in a position to describe our dispersion model. We will find it convenient in our development to deal initially with the crosswind integrated concentration

$$\overline{C}^y = \int_{-\infty}^{\infty} C(x,y,o)\,dy \qquad (4)$$

With (4) we can avoid discussion of plume intermittency in the crosswind direction.

Figure 1 shows a schematic of the physical system being considered. Based on visual evidence of the behaviour of the looping plume we will assume that we can separate the small scale spreading of the plume about its centerline and the larger scale up and down motion. The vertical meandering of the plume is associated with the convective updrafts and downdrafts extending through the depth of the PBL. As these downdrafts (or updrafts) have relatively long lifetimes (Lamb, 1978) it is reasonable to assume that a plume segment emitted into a downdraft will remain in it until it impinges on the ground. The figure illustrates such a situation. Note that the vertical velocity of the plume can be resolved into an upward acting buoyant velocity and an opposing downdraft velocity which eventually brings the plume down to the ground. As the emission point is taken to be well above the shear dominated surface layer most of the

downward travel of the plume occurs in a region in which the velocity (and potential temperature) is virtually uniform.

It is reasonable to assume that a nonzero concentration (crosswind integrated) is detected at a receptor x_r whenever the plume impinges on the ground at a distance $x \leq x_r$. Then if $P_d(x)$ is the probability density of plume impingement, the fraction of the time f the plume is seen at x_r is given by

$$f = \int_0^{x_r} P_d(x,\nu)dx \qquad (5)$$

In (5), ν refers to variables such as stack height, buoyancy and atmospheric turbulence which determine P_d.

It is always possible to associate an average vertical dimension σ to the collection of plume segments detected at x_r. Then, for a given wind speed u in the mixed layer we can express the average plume segment concentration at x_r as

$$C_p \sim \frac{Q}{u\sigma} \qquad (6)$$

where Q is the emission rate. Note that Q/u is the mass per unit length of the plume segment.

We assume that the ensemble averaged concentration can be written as

$$\overline{C}^y(x_r,o) \sim \frac{Qf}{u\sigma} \qquad (7)$$

Note that (7) implies that we are modeling the concentration time series at x_r by top-hat profiles whose constant magnitude is given by (6). In other words, the concentration at x_r is either zero or C_p. We point out that Davidson and Halitsky (1958) based a successful

dispersion model on this idea.

In order to be able to use (7) we need formulations for f and σ. As plume impingement can occur at any downwind distance ranging from 0 to ∞, a convenient choice for $P_d(x)$ is the lognormal distribution. The precise form of $P_d(x)$ is not expected to be critical in computing $\bar{C}^y(x_r,o)$ as f depends on the integral of the distribution. Then, we can express f as

$$f = \frac{1}{\sqrt{2\pi}\ell n s_g} \int_o^{x_r} \exp\left[-\left(\frac{\ell nx - \ell nm_g}{2\ell n^2 s_g}\right)^2\right] d(\ell nx) \qquad (8)$$

In (8), m_g and s_g are the geometric mean and standard deviation of the lognormal distribution. These parameters can be estimated by examining the results of numerical experiments by Lamb (1978). His study shows that the plume centerline descends when particles are released from an elevated source. The rate of descent of the centerline (locus of the maximum crosswind integrated concentration) is approximately 0.5 w_*. Then, for particles released at a height h_s, the plume centerline impinges at a distance wuh_s/w_* for the source. Briggs (1975) had a similar picture in mind when he proposed the "touchdown" model for plume rise. According to him the buoyant plume rises relative to a region of convective downdrafts. As the buoyant plume rise rate descreases with time the downdrafts eventually bring the plume to the ground at a distance x_i given by the solution of the following equation

$$\frac{\alpha F^{1/3} x_i^{2/3}}{u} - \frac{w_d x_i}{u} = -h_s \qquad (9)$$

where F is the buoyancy parameter and w_d is the downdraft velocity

which is about 0.5 w_*. The first term on the left is the buoyant rise and the second term represents the effect of convective downdrafts. Some preliminary studies (Venkatram 1980) indicate that the constant α in (9) is $\simeq 1.0$.

In view of the preceding discussion we feel that it is reasonable to assume that the mean impingement distance m_g is proportional to x_i. The model testing, described in a later section, indicated that the simplest relationship $m_g = x_i$ was adequate. We can estimate s_g by using Lamb's (personal communication) results on the statistics of convective velocities in the PBL. He found that the magnitude of the downdraft velocity one standard deviation away from the mean ($= 0.5\ w_*$) was approximately $0.75\ w_*$ ($= 1.5\ w_d$). The impingement distance corresponding to $0.75\ w_*$ would be a lower limit on possible plume impingement distances. We can then approximate s_g by

$$s_g = \frac{x_i (w_d = 0.5\ w_*)}{x_i (w_d = 0.75\ w_*)} \qquad (10)$$

It is interesting to note that for the cases considered, s_g computed from (10) was around 2, the value used in an earlier version of this model (Venkatram, 1980).

For the behaviour of σ we propose

$$\frac{\sigma}{z_i} \sim X \quad ; \text{ small } X \qquad (11a)$$

$$\frac{\sigma}{z_i} \sim \text{constant} \quad ; \text{ large } X \qquad (11b)$$

Equation (11b) reflects the observation that at large X the vertical spread is limited by the capping inversion at z_i.

A plausible interpolation for σ between the limits for small and large X can be written as

$$\frac{\sigma}{z_i} = A\left[1 - \exp(-1.5\ X)\right] \qquad (12)$$

where A is a constant to be determined from the subsequent analysis. The constant 1.5 in (12) was chosen on the basis of model testing described in a later section. Also, it is seen that for $X > 3$, σ is within 1% of its maximum value. This result agrees with the observations of Willis and Deardorff (1976).

We can now write the expression for the centerline ground-level concentration as

$$C(X,o,o) = \frac{BQf(X)}{u\sigma_y\sigma} \qquad (13)$$

We can determine the constant B in (13) by noting that the expression for C(X,o,o) should reduce to that corresponding to the well-mixed PBL for large X

$$C(X,o,o) = \frac{Q}{\sqrt{2\pi}\ u\sigma_y z_i} \qquad (14)$$

From (14) we see that $B/A = 1/\sqrt{2\pi}$. Note that (14) implies that the concentration distribution in the crosswind direction is Gaussian, a description which is adequate according to the tank experiments of Willis and Deardorff (1976).

In a recent study Nieuwstadt (1980) showed that under convective conditions $\sigma_y \sim X$ for X as large as 4. Moore (1975) also found this linear behaviour in his measurement of σ_y values due to elevated sources. Based on these studies we selected the following simple form for σ_y

$$\sigma_y/z_i = 0.45\ X \qquad (15)$$

The constant multiplying X in (15) was suggested by Willis and Deardorff (1978).

It is useful to note that the expressions for the σ's do not include the effects of self-induced spread due to plume buoyancy. The model testing described in a later section indicated that these effects were minor.

It should be apparent from the preceding discussion that each stage of model development relied heavily on comparison with concentration observations. Thus, this model is essentially a concise description of the observations made under a variety of meteorological and stack conditions. We point out that a model is of little value if it has to be "tuned" each time the dispersion conditions change. As will be seen in the next section, our model has been applied to four independent sets of data with no-site specific "tuning".

3. Model Testing

The model was tested with four sets of data. Two of them, reported by Weil (1977), refer to measurements made in the vicinity of the Dickerson and Morgantown power plants situated in Maryland. The remaining data consists of measurements made around the INCO nickel smelter in Sudbury, Ontario. Simultaneous meteorological data were also obtained during these field studies.

For the sake of completeness, we will describe some of the relevant information given in Weil's report. The coal-fired Dickerson plant consists of three 185 MW generated units with two 122 m stacks, 60 m apart. It is situated in the rolling terrain of Montgomery

County. Measurements at the Dickerson plant extended from October 1972 through April 1973.

The Morgantown power plant is also situated in relatively flat terrain next to the Potomac River in southern Charles County. It has two 575 MW units exhausting through two 213 m stacks, 76 m apart. Measurements at the plant were made during February 1975 through June 1975.

The INCO (International Nickel Company) smelter is situated on flat ground in Sudbury, Ontario. There are a number of small lakes in the vicinity of the plant. Waste gases from the smelter are exhausted through a 381 m stack. The high sulphur content of the local nickel ore results in the emission of approximately 3000 tons of SO_2 per day. The first field experiment to study the concentrations associated with this emission was conducted during a two-week period in June 1978. A second field study was undertaken during the week of August 16, 1979.

The method of measurement of SO_2 was similar in all four field studies. An instrumented mobile van was used to measure ground-level SO_2 concentrations. Using available roads, repeated passes were made across the direction of plume travel. The traverses lasted from $\frac{1}{2}$ to 1 hour and resulted in about 6 to 10 instantaneous concentration profiles. Some of the traverses in the Sudbury field study were done with an instrumented twin-engined Aztec aircraft flying at tree-top level ($\sim$ 30 m).

Concentration profiles obtained from the traverses were combined to form an Eulerian averaged profile corresponding to an averaging time of approximately 1 hour. The maximum of this composite profile was taken to represent the ground-level centerline concentration. These centerline concentrations were compared with predictions from

our model. Following Deardorff and Willis (1975) we used data corresponding to the range $1.5\ w_* \leq u \leq 6\ w_*$ to ensure the applicability of convective scaling.

As the surface heat flux was not measured, we assumed that it was 0.3 times the incoming solar radiation. We believe that this is not critical as the heat flux is used in the computation of the convective velocity w_* which depends on the one-third power of the heat flux.

Concentration observations were compared with model predictions using the following three steps:

1. Compute percentage of predictions within a factor-of-two of the observations. The factor-of-two criterion is based on experience with dispersion modeling and is the time-honored method of testing model performance, (A Position Paper of the AMS 1977 Committee on Atmospheric Turbulence and Diffusion Model). Predictions meeting this accuracy criterion were further tested using curve fitting procedures.

2. Regress observations on predictions using the following equation:

$$C(\text{observed}) = a + bC(\text{predicted}) \qquad (16)$$

The value of the coefficient of determination r^2 is an indication of the performance of the model. Furthermore, the regression coefficients 'a' and 'b' should not be significantly different from their expected values of 0.0 and 1.0 respectively.

3. Regress observations on predictions using the equation:

$$C(\text{observed}) = a\left[C(\text{predicted})\right]^b \qquad (17)$$

Equation (17) would be relevant for model testing if observations are lognormally distributed about the predicted ensemble mean. As observations indicate that this is indeed the case (Csanady, 1973) we feel that the r^2 associated with (17) is a good test of model accuracy. Note that the expected value of 'a' and 'b' is unity.

Table 1 summarizes the results of model testing on three sets of data. It is seen that model predictions compare well with observed concentrations. More than 80% of the predictions are within a factor-of-two of the measurements. The value of r^2 for the Dickerson data set is above 0.70. This indicates a high degree of association between model predictions and observations. For the Morgantown data there is a tendency for the model to underpredict slightly although the r^2 is as high as 0.80 for the logarithmic correlation analysis.

For the 1978 Sudbury data, the model does not perform as well as it does for Dickerson and Morgantown. This could be related to the fact that our assumption of constant downdraft velocity might be questionable when the emission point is in the upper part of the convective PBL. Recall that the Sudbury stack is 381 m tall.

Figures 2, 3 and 4 illustrate the details of the comparison between model predictions and observations. In Fig. (2a) we have plotted the ratio of C(observed) to C(predicted) against X/X_i. It is seen that the model performs as well for $X/X_i > 1$ as it does for $X/X_i < 1$. This gives us some confidence in our choice of the log-normal distribution to "smear" the concentration distribution around the mean impingement distance x_i. The scattergram of Fig. (2b) shows in more detail the excellent agreement between predicted and

observed concentrations.

It is seen from the Table that the averaging times for most of the observations are less than one hour. Furthermore, the concentrations represent averages derived from about six instantaneous values corresponding to ground level traverses. In view of this (See Venkatram, 1979 for a detailed discussion) substantial deviations of observed concentrations from predicted ensemble means are not unexpected. However, as seen in Fig. (4a), this scatter is well within the acceptable norms (see AMS position paper on this subject, Bulletin of the American Meteorological Society). In fact, 80% of the data is within a factor of 1.5 of the predictions.

In performing a regression analysis between observations and predictions we have chosen only those data points which meet the factor-of-two criterion. This filtering is justifiable, in our opinion, only if the rejected data points are a small percentage of the observations. Furthermore, this process ensures (approximately), that the expected variances of the observed concentrations about the predictions are comparable in magnitude. Note that linear regression is valid only if this condition is satisfied (Neville and Kennedy, 1964). Figure (3a) indicates, as seen before, that the model slightly underpredicts concentrations for the Morgantown data set. However, better than 65% of the predictions are within a factor of 1.5 of the measured concentrations. The high degree of association between model results and observations is also evident in Fig. (3b).

The details of the meteorological and source conditions for the Dickerson and Morgantown concentration observations are given elsewhere (Venkatram, 1980). In this paper we only present the relevant information for the observations made in Sudbury, Ontario.

Note that (Table 2) $u \leq 6\ w_*$ for all the data indicating that the PBL is dominated by buoyant production of turbulence. This also justifies the use of convective scaling (Deardorff and Willis, 1975) in the analysis of dispersion.

Figure 4b illustrates the comparison between observed and predicted concentrations. Considering the expected variances in measurements the comparison is gratifying. In addition to the r^2 being as high as 0.6, the best fit values of 'a' and 'b' are very close to their expected values.

Table 2 gives the relevant information for the 1979 field study in Sudbury. Note that the mixed layer winds are small compared with those measured during the 1978 experiment. This, as we shall see later, has implications with regard to our ability to predict observed concentrations. An examination of the Table indicates that 94% of the model estimated values are within a factor-of-two of the observed values. However, it is seen that the r^2 value is only 0.1. Thus it would seem that although the model meets operational requirements, it does not satisfy statistical tests. However, we will see in the next section that linear correlation analysis (r^2) is not always appropriate and in many cases cannot tell whether or not a model is working.

4. Summary of Model Equations

At this point it is useful to summarize the equations on which our model is based.

$$\overline{C}(X,o,o) = \frac{1}{\sqrt{2\pi}\ \overline{\sigma}\ \overline{\sigma}_y} \qquad (18a)$$

$$\overline{C} = Cz_i^2 u/Q; \quad X \equiv w_* x/z_i u \qquad (18b)$$

$$\bar{\sigma}_y = \sigma_y / z_i = 0.45\ X \tag{18c}$$

$$\bar{\sigma} \equiv \sigma / z_i = \left[1 - \exp(-1.5\ X)\right] \tag{18d}$$

$$f(X) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{p} \exp(-t^2/2)\,dt \tag{18e}$$

$$p = \ell n(X/X_i) / \ell n s_g \tag{18f}$$

$$X_i = w_* x_i / z_i u \tag{18g}$$

In (18f), the mean impingement distance x_i is the solution of

$$F^{1/3} x_i^{2/3} - w_d x_i + h_s u = 0 \tag{19a}$$

$$w_d = 0.5\ w_* \tag{19b}$$

$$s_g = \frac{x_i (w_d = 0.5\ w_*)}{x_i (w_d = 0.75\ w_*)} \tag{19c}$$

The results from an earlier paper (Venkatram, 1980) indicate that using a constant value $s_g = 2.0$ yields acceptable model predictions.

It is useful to point out that the expression for the ground-level concentration when the PBL is well-mixed is simply

$$C(x,o,o) = \frac{0.9\ Q}{w_* z_i x} \tag{20}$$

Note that (20) is independent of the wind speed u. In an earlier paper (Venkatram, 1980) we showed that this simple expression can provide acceptable estimates of concentrations even for distances as small as X = 0.4. However, the acceptability of a concentration prediction depends on the particular application of the model. For example, estimates better than a factor-of-two might be necessary for supplementary emission control during "adverse" meteorological

conditions. However, as we shall see in the next section, there is a limit to our ability to predict observed concentrations even if we have a "perfect" model.

5. Comparison of Concentration Estimates with Observations

Even if we can make reliable estimates of concentrations, the nature of the convective boundary layer presents us with problems when we attempt to compare these estimates with measured concentrations. We have to realize that computed concentrations correspond to ensemble averages while measured concentrations represent averages over a limited set of "concentration" events. It is possible to show (Venkatram, 1979) that the expected deviation of the observed average concentration from the predicted ensemble mean can be written as

$$\varepsilon^2 \simeq \frac{2(\Gamma - 1)\tau_E}{T} \qquad (21)$$

In (21), ε is the deviation as a fraction of the ensemble mean concentration, Γ is the ratio of the instantaneous peak to the ensemble mean at the receptor under consideration, τ_E is the Eulerian time scale governing dispersion and T is the averaging time (sampling time to be precise). In the convective boundary layer τ_E can be approximated by z_i/u so that (13) reduces to

$$\varepsilon^2 \simeq \frac{2(\Gamma - 1)z_i}{uT} \qquad (22)$$

Close to the stack Γ can be as large as 100 (see Gifford, 1959). The ratio increases away from the centerline to relatively large values at the edge of the plume. At large downwind distances Γ approaches an asymptotic value of 2. Eq. (22) implies that comparison of

observations with predictions in the vicinity of x_i is not straightforward. If we take $\Gamma = 10$ at x_i (Pasquill, 1974), $u = 5$ ms^{-1} and $z_i = 1500$ m we find that $\varepsilon \simeq 1.22$ for a typical averaging time of one hour. In view of this, it might be necessary to average over several observations before any meaningful model validation can be done. It should be pointed out that this problem with comparison with observations is related to the relatively large horizontal length scales ($\sim z_i$) found in the convective boundary layer. In other words, the large convective eddies and wind speed determine the duration of a concentration event recorded at a receptor. Thus, for a fixed averaging time, the number of events N_E which constitute the observed average can be approximated by

$$N_E \simeq \frac{Tu}{\ell} \qquad (23)$$

To get an idea of a typical value for N_E let us take $\ell = 1500$ m and u to 5 ms^{-1}. From (23) we find that the observed concentration averaged over one hour ($T = 3600$ s) corresponds to only 12 concentrations events. This tells us that we are likely to have problems in predicting short-term concentrations during convective conditions.

It is noted from (22) that the deviation between model predictions and observations increases as the wind speed decreases. This could explain the relatively poor r^2 for the 1979 field study in Sudbury. To understand this better, consider the expression for r^2

$$r^2 = 1 - \frac{\text{unexplained variance}}{\text{variance of observations}} \qquad (24)$$

If we denote the average of the observations by $\overline{C}$, the unexplained variance of a "good" model would be approximately $\varepsilon^2\overline{C}^2$. Then, even if the model is working r^2 will be low if the variance of the observations is comparable to $\varepsilon^2\overline{C}^2$. Note that ε^2 is determined by

the inherent nature of turbulence and has nothing to do with measurement or modeling errors. It is readily seen from the data presented in Table 3 that the expected variance $\varepsilon^2\overline{C^2}$ between observations and model estimates is comparable to the variance of the observed concentrations. Thus, the low value of r^2 is expected from theory. Our analysis indicates that r^2 is a valid indicator of model performance only if the expected variance between observations and predictions is much smaller than the variance of the measured concentrations.

We see from (22) that ε^2 is inversely proportional to the averaging time T. This means that model performance will improve with averaging time. However, we should note that the magnitude of T is limited by the time scale of the evolution of the planetary boundary layer. Beyond T ~ 1 hour nonstationarity effects will contaminate observations. To illustrate the role of averaging time in determining model predictability we have plotted the ratio C(observed)/C(predicted) for the 1979 Sudbury data against time of traversing which corresponds roughly to T. In spite of the scatter in the data, there is a clear trend indicating improvement of model predictions with averaging time.

Our discussion clearly emphasizes the problems related to predicting short-term concentrations in the convective boundary layer. The implications of this will be discussed in more detail in the next section.

6. Applications of the Model

The obvious application of the model is in supplementary emission control which works as follows:

Meteorological inputs to the model are predicted a few hours ahead of time. Then the model is used to determine the emission rate which will ensure that the maximum expected concentration (predicted) will be below the local air quality standard. Cutbacks in emission are implemented if an exceedence is likely. The success of this type of emission control depends upon a) the ability to forecast meteorological variables and b) the validity of the model used to predict the concentration. We will confine our discussion to point (b).

A validated physically correct model is necessary for effective emission control. The convective dispersion model described in this report is clearly suitable for this application. However, as we pointed out earlier, a model prediciton will deviate from the observed value. Furthermore, this deviation is large under low wind speed conditions when the maximum concentrations are likely to be at their highest. This suggests that a model can provide guidance rather than the prediction required for emission control. Specifically the model tells us that the most important meteorological variables are z_i, w_* and u. The model prediction based on these variables will provide information on the range of values in which the observed concentrations will lie. The precise use of this concentration range will depend on the economics of the supplementary emission control program. What we want to emphasize is that even if we could forecast meteorological variables accurately, we cannot have a perfect emission reduction program. There are bound to be a certain number of exceedences of the air quality standard.

Another application of the model is in the prediction of long-term averages. In this case, there is good reason to believe

that deviations between observations and predictions will be minimized in the averaging involved in computing the long-term (annual) average. This filtering of the errors will occur only if the short-term sub-model in the long-term model is capable of predicting the correct ensemble mean. The model presented in this report satisfies this criterion.

7. SUMMARY

This report presents a model to describe dispersion of pollutants emitted from a point source into a convective boundary layer. The model is applicable to the INCO plume which causes high ground-level concentrations primarily during convective conditions on sunny days. We should point out that conventional Gaussian models based on the Pasquill-Gifford curves do not work under these conditions. The model described here represents a new approach to dispersion modelling.

The model uses some of the most recent understanding of dispersion in the convective boundary layer. Furthermore, model predictions have been compared with field data collected in Sudbury and elsewhere. The results of the comparison are very encouraging. The model is simple to use as it depends on routinely available meteorological measurements. The mixed layer height z_i can be estimated from morning temperature soundings and surface temperature forecasts. It can also be predicted with relatively simple models such as the one described by Carson and Smith (1974). Similarly, the convective velocity scale w_* can be readily related to the solar heat flux or the mixed layer height using formulations described in Venkatram (1978). The model is suitable for operational use in a supplementary emission control program such as the one used by INCO.

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TABLE 1. Summary of model testing for the Dickerson, Morgantown and Sudbury data sets. Numbers in parenthesis are the standard deviations.

Data Set Name	No. of Data Points	Percentage Meeting Factor-of-two criterion	Mean Value of C(obs)/C(pred) (filtered data set)	Linear r^2	Linear a(μgm^{-3})	Linear b	Logarithmic r^2	Logarithmic a	Logarithmic b
Dickerson	26	85	0.98(0.34)	0.70	-0.15	0.98	0.74	0.91	1.00
Morgantown	22	86	1.20(0.37)	0.65	18.86	0.87	0.80	2.21	0.84
Sudbury	25	80	1.02(0.27)	0.53	9.95	1.00	0.60	0.89	1.20

TABLE 2. Listing of meteorological and stack conditions for the Sudbury concentration measurements during June 1978. Model predicts the impingement distance x_i and C(predicted).

Run No.	DA	MO	YR	START TIME	END TIME	F (m^4s^{-3})	Q (gs^{-1})	x (m)	z_i (m)	w_* (ms^{-1})	u (ms^{-1})	x_i (m)	C(OBS) (μgm^{-3})	C(PRED) (μgm^{-3})	C(OBS)/C(PRED)
1	10	06	78	13:45	14:32	2082	28213	3100	1040	2.13	11.3	9372	208	241	0.86
2	10	06	78	14:02	15:00	2149	32224	39000	940	2.16	11.7	9479	260	361	0.72
3	10	06	78	15:56	17:12	2072	22958	32000	740	2.31	10.2	7650	494	373	1.32
4	11	06	78	16:10	17:11	1897	22958	3000	1540	2.80	13.8	6987	182	241	0.75
5	13	06	78	13:34	15:00	2590	33330	9200	1640	2.58	10.5	6994	520	593	0.88
6	13	06	78	13:01	13:35	2703	33884	15500	1640	2.48	8.9	6744	390	444	0.88
7	13	06	78	16:30	17:04	2481	27383	5100	1840	2.66	10.3	6493	780	519	1.50
8	13	06	78	16:44	17:20	2481	27383	18000	1840	2.66	11.5	7029	832	272	3.05
9	13	06	78	17:23	17:54	2489	30426	13800	1940	2.64	10.3	6576	312	367	0.85
10	13	06	78	10:28	12:43	2761	32086	6000	1140	1.93	9.0	10543	572	552	1.04
11	14	06	78	13:03	13:26	2768	35681	12000	1740	2.28	7.6	7082	832	553	1.50
12	14	06	78	13:31	14:05	2753	35681	21000	1740	2.35	6.0	5792	390	363	1.07
13	14	06	78	16:00	16:30	2477	25171	18000	1440	2.54	5.8	4750	156	336	0.46
14	14	06	78	16:03	16:49	2425	23649	38000	1340	2.54	5.7	4662	910	164	5.54
15	14	06	78	16:34	17:10	2534	37894	23500	1440	2.55	5.6	4654	260	391	0.66
16	20	06	78	12:02	12:43	2375	24479	18000	790	2.22	6.8	6535	520	651	0.80
17	20	06	78	12:27	13:24	2445	18671	6500	940	2.32	7.0	6232	520	636	0.82
18	20	06	78	12:53	13:38	2416	21575	29000	840	2.40	7.0	5854	338	329	1.03
19	20	06	78	16:18	17:26	2454	26830	23500	1590	2.38	8.3	6676	312	265	1.18
20	23	06	78	12:56	13:23	1965	14660	15500	1240	2.37	5.0	5033	338	277	1.22
21	23	06	78	13:05	14:32	1854	11064	4100	1240	2.44	5.5	4436	286	412	0.69
22	23	06	78	17:02	17:55	2327	22820	10500	1340	2.55	9.0	6195	624	476	1.31
23	27	06	78	15:37	16:38	2495	28075	4700	1690	2.51	9.0	6494	234	558	0.42
24	27	06	78	16:21	16:57	2495	28075	20000	1640	2.55	8.1	5889	390	295	1.32
25	27	06	78	17:08	17:39	2474	28628	32000	1740	2.58	8.1	5762	416	178	2.33

TABLE 3. Summary of model testing for field data collected during June 1979 field study in Sudbury.

Time of Sample	Average Time (min)	No. of Passes	x(m)	Q (gs^{-1})	z_i (m)	w_* (ms^{-1})	u (ms^{-1})	F (m^4s^{-3})	C(Obs) (μgm^{-3})	C(Pred) (μgm^{-3})	$\frac{C(Obs)}{C(Pred)}$
16/08/79											
1336-1448	72	9	5000	12800	1100	2.05	3.4	1920	390	555	0.70
1458-1525	27	4	5500	15300	1530	2.24	4.1	1918	728	486	1.50
1542-1645	63	8	5500	20830	1300	1.93	4.5	1967	572	648	0.88
22/08/79											
1425-1457	32	4	16700	17800	1000	2.03	3.2	2004	494	451	1.10
1510-1532	22	3	14400	15600	1150	2.01	3.4	1991	702	390	1.80
1425-1532	67	7	14500	16100	1100	2.01	3.7	1991	520	415	1.25
1539-1624	45	10	14000	12200	1200	1.99	3.6	1990	364	298	1.22
1631-1735	64	6	13100	13100	1200	1.83	3.7	2037	338	341	0.99
1541-1600	19	3	15600	13300	1200	2.02	3.6	1978	754	297	2.54
1612-1700	48	5	15100	11900	1200	1.89	3.7	2019	442	280	1.58
1541-1711	90	9	15100	12200	1200	1.87	3.7	1990	390	289	1.35
1541-1700	79	8	15100	12100	1200	1.87	3.7	1990	416	286	1.45
1725-1752	27	4	14700	15600	1200	1.66	3.8	2013	702	369	1.90
1800-1826	26	5	14500	18500	1200	1.47	3.8	2024	390	447	0.87
1725-1826	61	9	14600	16700	1200	1.52	3.8	2011	442	405	1.09
25/08/79											
1303-1330	27	6	9100	23100	1150	1.62	8.4	2250	676	429	1.57

Percentage within a factor-of-two of observations = 94%

$r^2 = 0.1$

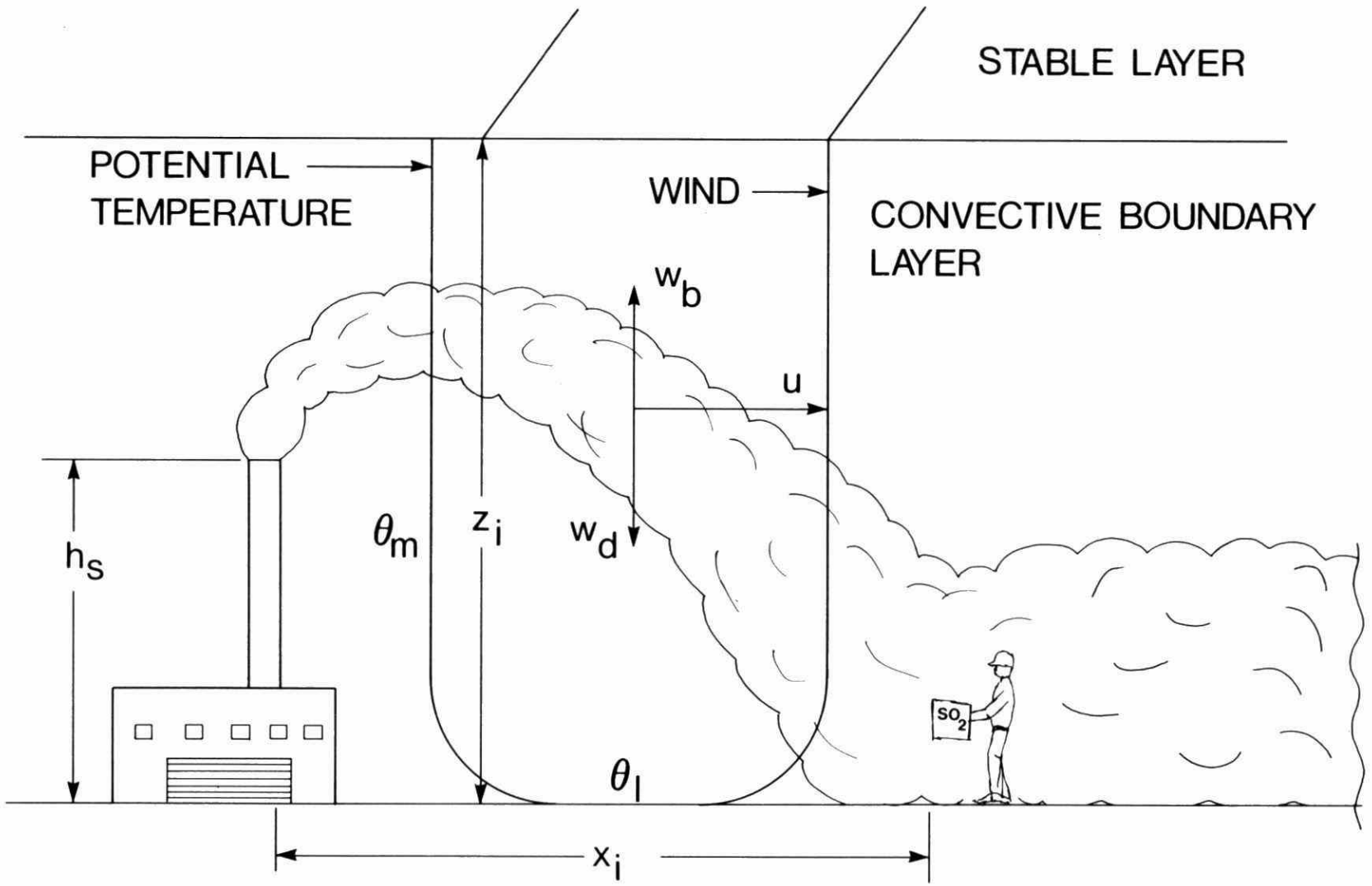

Figure 1. Schematic of physical system under study

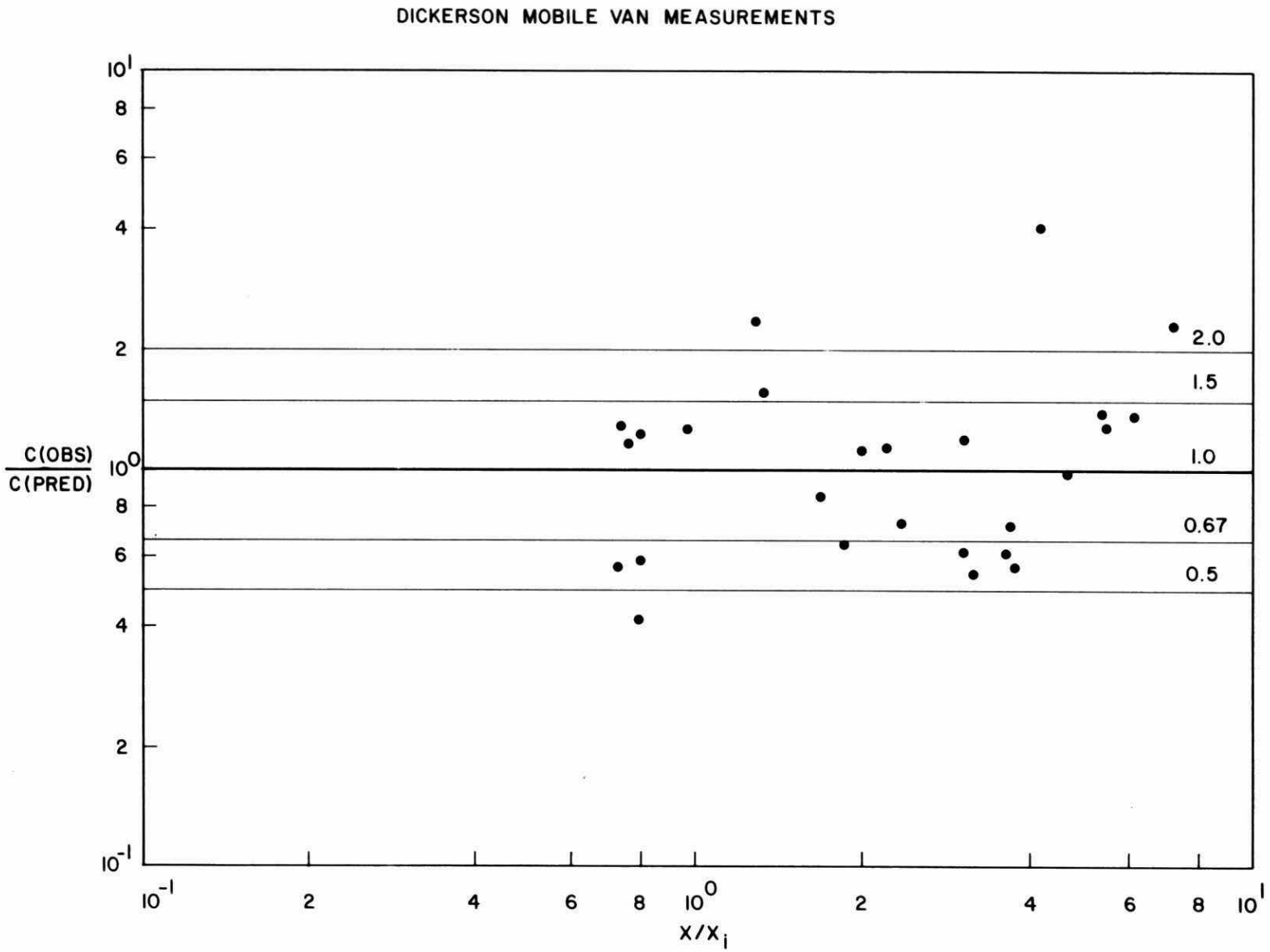

Figure 2a. Variation of the ratio C(observed)/C(predicted) as a function of X/X_i. Horizontal lines correspond to the selected values of the ratio. Data set refers to the Dickerson Power Plant.

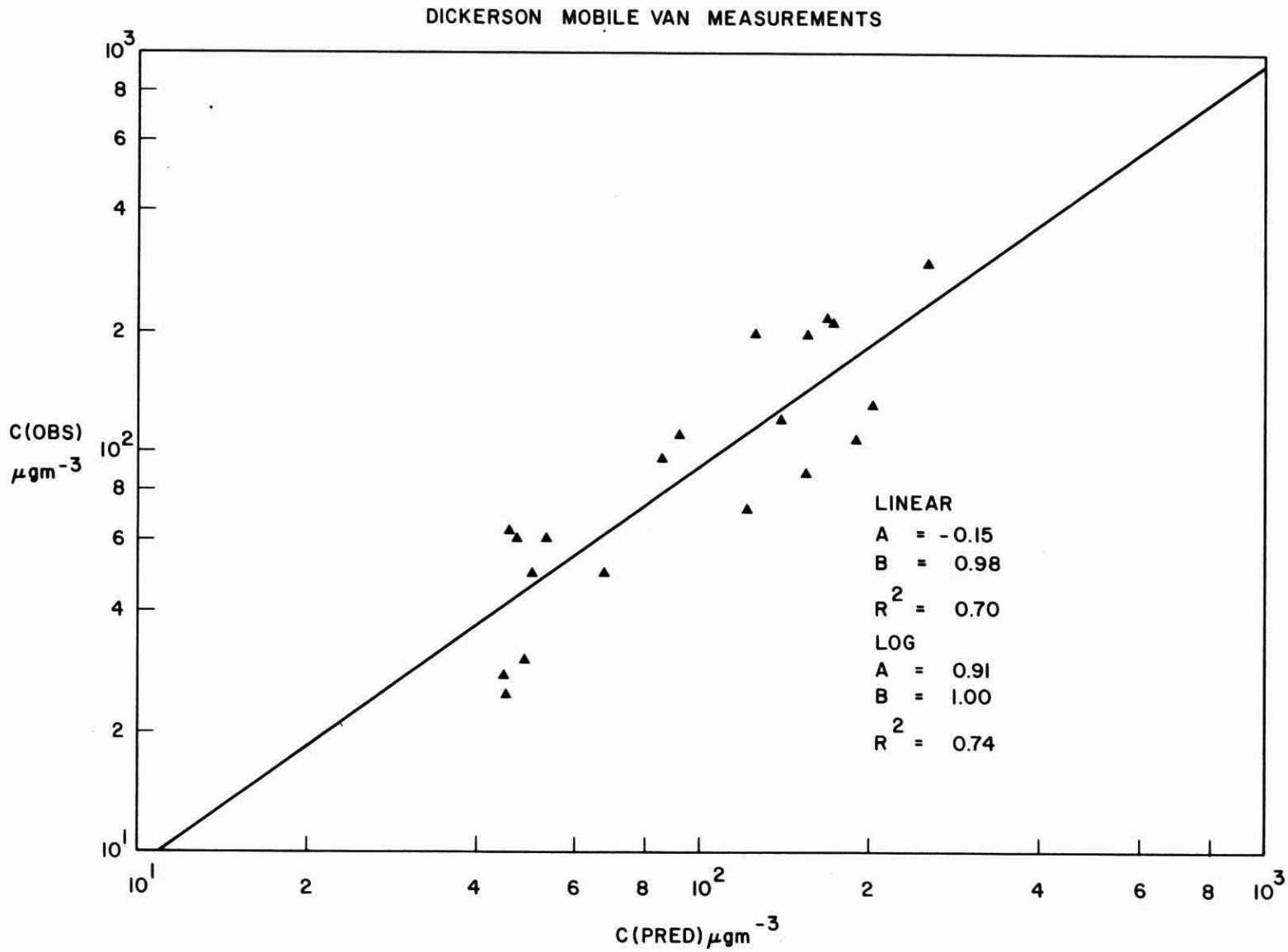

Figure 2b. Scattergram of predicted concentrations against observed concentrations. Data set refers to measurements around the Dickerson Power Plant. Only data meeting the factor-of-two criterion have been used. The best fit line corresponds to regression of logtransformed concentrations.

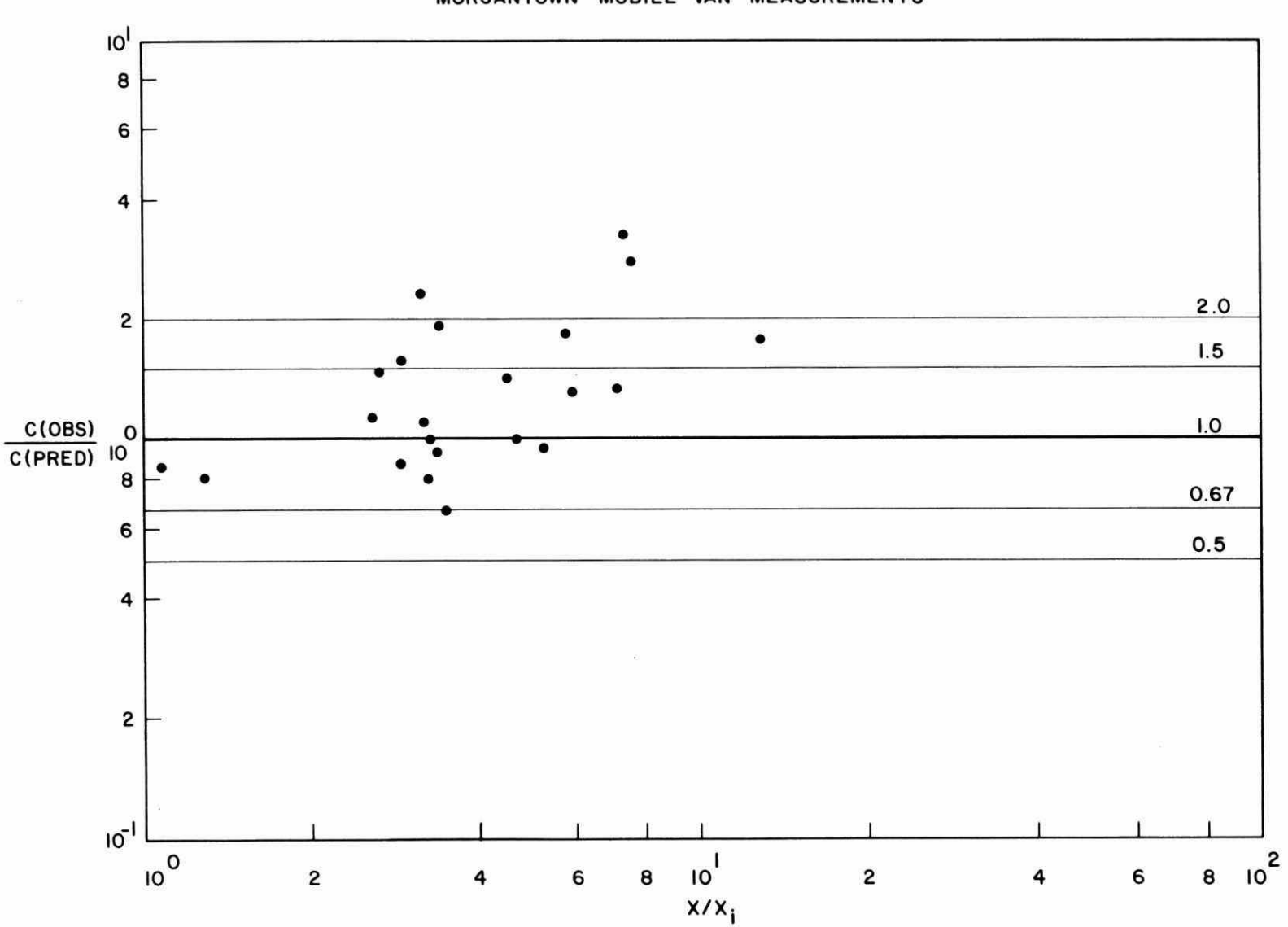

Figure 3a. Same as 2a except for Morgantown Power Plant.

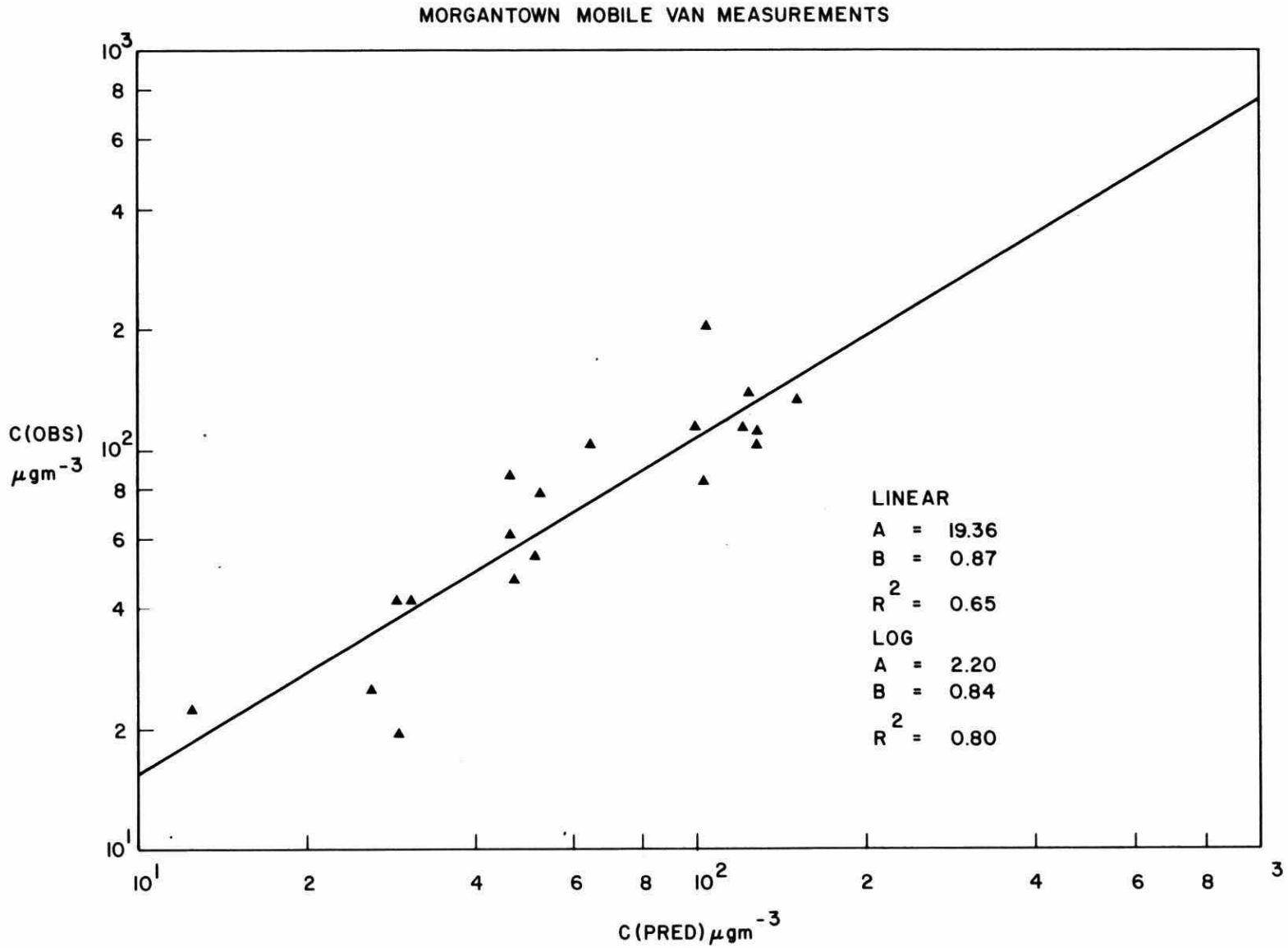

Figure 3b. Same as 2b except for Morgantown Power Plant.

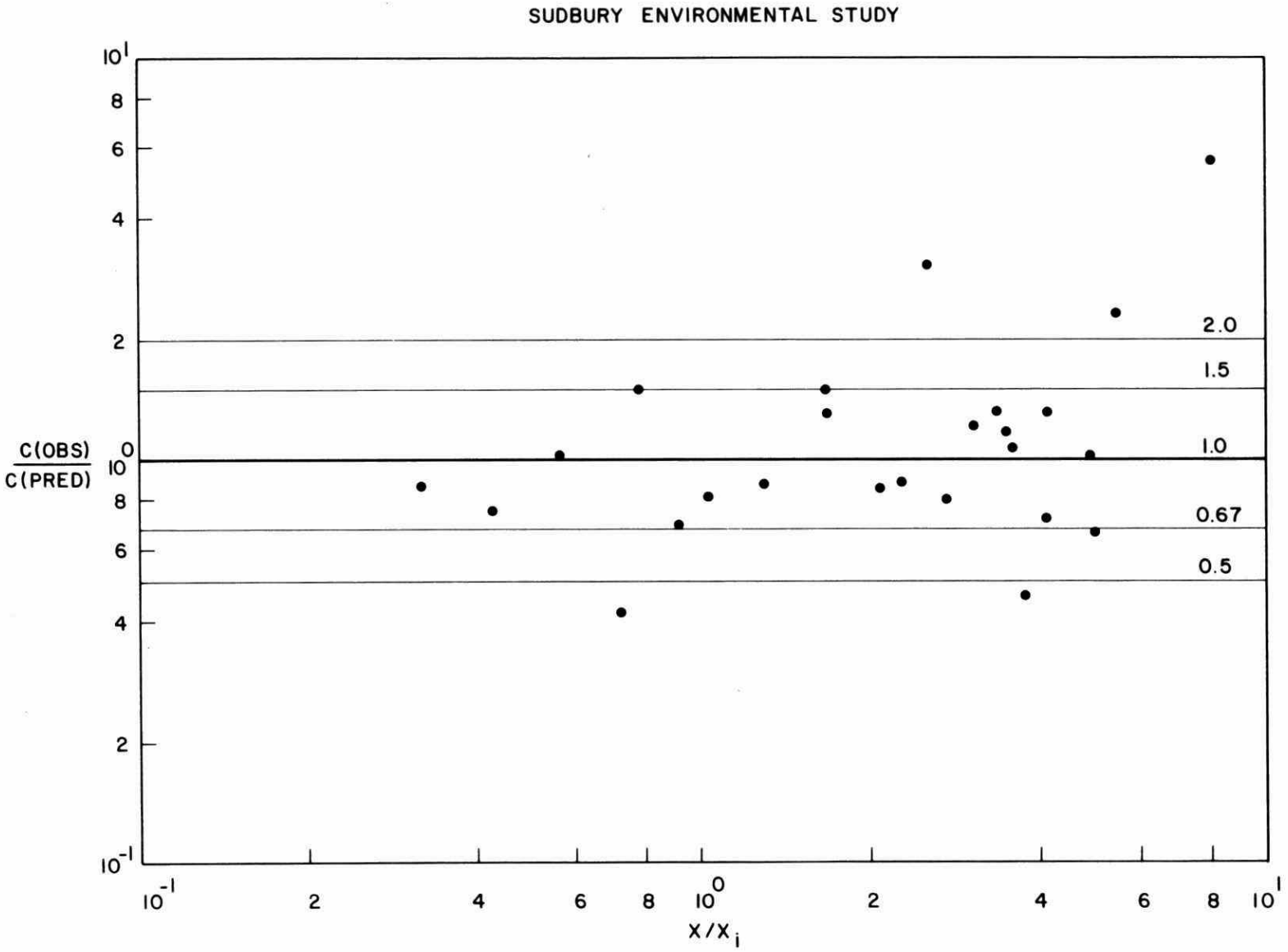

Figure 4a. Same as 2a except for Sudbury.

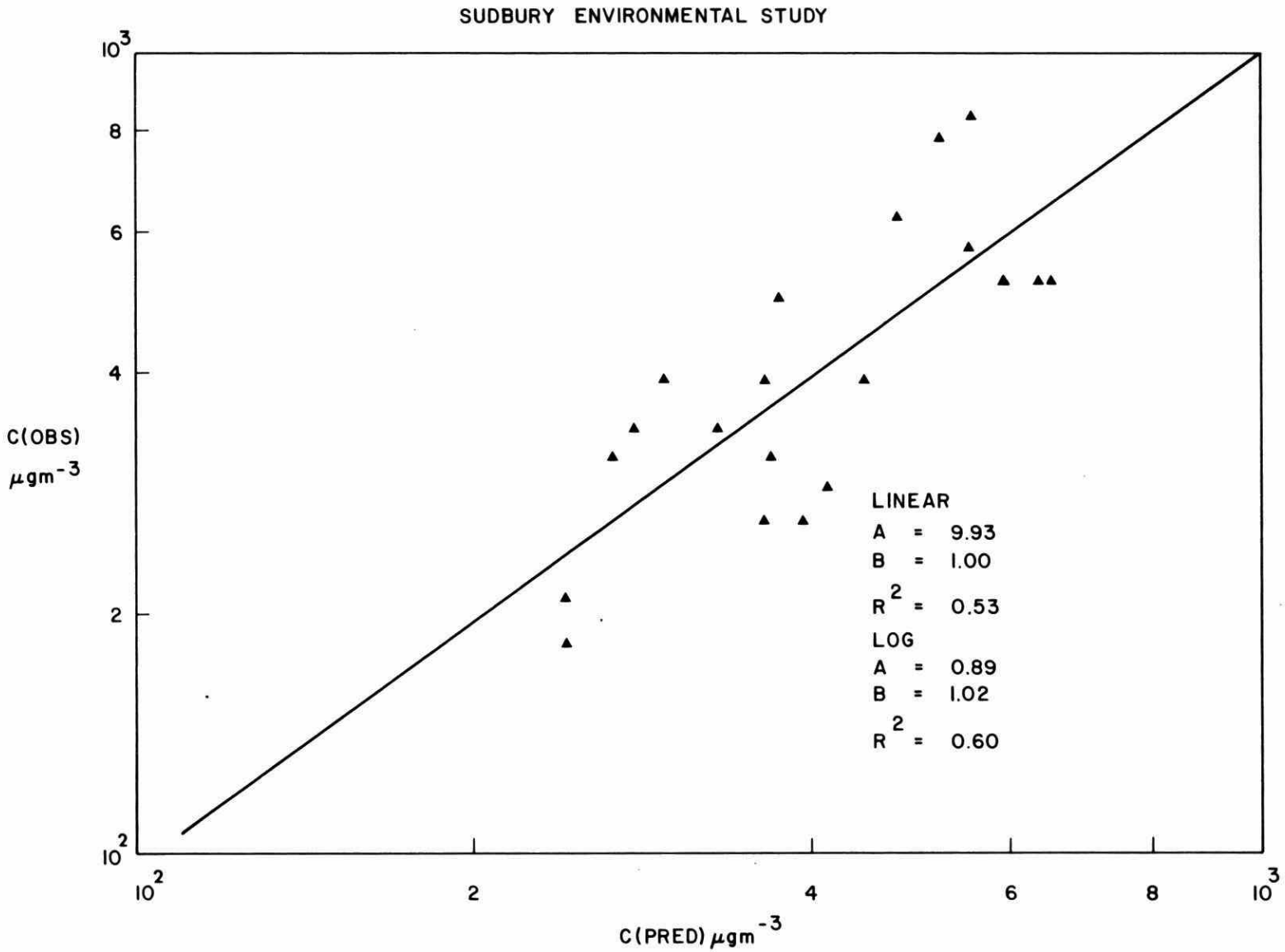

Figure 4b. Same as 2b except for Sudbury

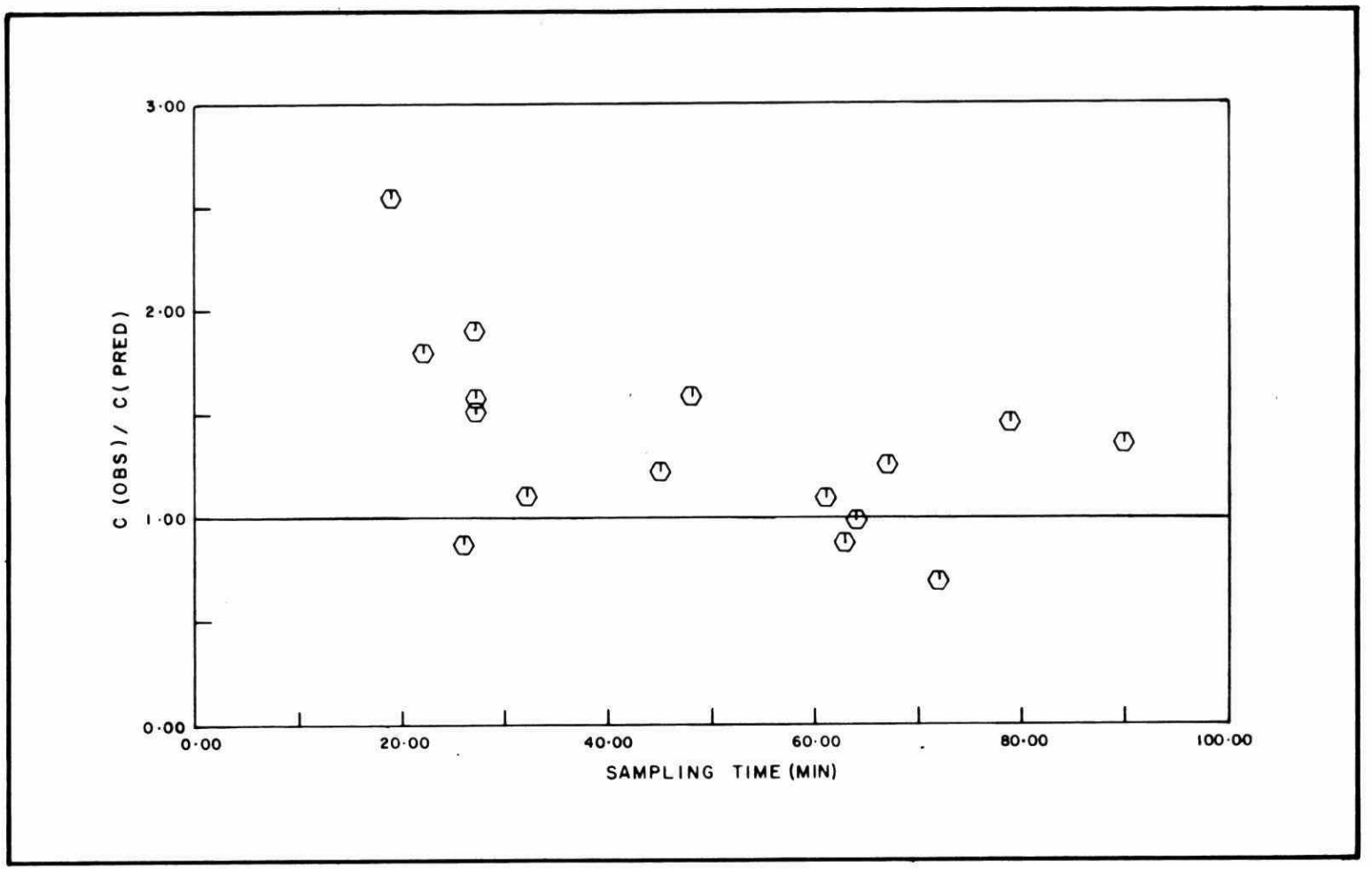

Figure 5. Variation of C(Obs)/C(Pred) with sampling time